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Basic Research Program

Rail Gun

SEMIANNUAL TECHNICAL REPORT

(Period Covering 1 July—31 December 1961)

28 FEBRUARY 1962

Prepared by W. R. GRABOWSKY
Advanced Propulsion and Fluid Mechanics Department
Aerodynamics and Propulsion Research Laboratory

Prepared for DEPUTY COMMANDER AEROSPACE SYSTEMS
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
Inglewood, California

LABORATORIES DIVISION • AEROSPACE CORPORATION
CONTRACT NO. AF 04(647)-930

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PREFACE

Progress in the Chemical Thermodynamics phase of the Basic Research Program is reported in Volume I.

ABSTRACT

Progress in the Rail Gun phase of the Basic Research Program for 1 July through 31 December is described. The performance of a rail gun propulsion system is examined from the standpoint of a satellite attitude control device. Estimates of the propulsive performance of the gun are made which are related to a rotation and angular acceleration that could be imparted to a given satellite. Some results are presented that would allow for a weight estimation of a specific system. Finally, some preliminary experimental data relative to the propulsive capability of the rail gun are presented.

CONTENTS

FIGURES

I. INTRODUCTION AND BACKGROUND

Some currently considered applications for satellites place severe requirements on attitude-control devices (e. g., 24-hour communications satellites). The attitude control device must operate reliably for years, produce large thrusts for the amount of propellant expelled (for jet producing devices), and possess a low total weight. An evaluation of possible propulsion systems for this application revealed that, in general, gaseous systems suffer from a reliability standpoint, i. e., the large amount of regulators and valves required produce potential leaks that decrease the probable operating time. In addition, cold gas systems possess excessive propellant storage weight as a result of the low I_{sp} of the engine. Thus, a system that utilizes a propellant that could be easily stored in a vacuum and that possesses a high I_{sp} would eliminate these difficulties. In particular, a system that could use wire, stored on a spool, appears attractive.

Extensive work is currently being done on exploding wire phenomena, and in some instances the wire plasmoid is being used as a propellant (e. g., Ref. 1). In all cases, capacitor discharges are used to explode wires with the initial capacitor potentials being on the order of 10 kilovolts. Acceleration schemes vary from a simple thermal expansion* to tailored geometries, such as a coaxial gun,[2] to the use of inherent plasma instabilities.[3] For the application considered here, the rail gun geometry was chosen because of the initial geometry of the propellant (wire) "slug."

The aims are to analyze and to optimize the performance of the gun as a propulsion system. Once this is done, a detailed investigation of the phenomena occurring within the gun will be pursued. For instance, the nature of the material being expelled by such discharges is of interest. All devices of this nature suffer from electrode and wall erosion. Thus, the actual mass flow through the device is unknown, and this unknown also exists in the I_{sp}. Further investigations of interest would be the nature of the discharge relative to the electric and magnetic fields that exist throughout the plasma.

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*Personal conversation with J. Webb, Electro-Optical Systems.

II. TECHNICAL PROGRESS

Analytical studies associated with pulsed plasma devices employing self-propelled plasmas (i.e., self-generated magnetic fields) are quite extensive. In general, for the circuit shown in Fig. 1a, the attack on such problems is universal and goes as follows.

Kirchoff's law for the circuit can be written:

$$V = V(L, I, x, R; t) \tag{1}$$

where

V = voltage

L = total inductance

I = current

x = distance along the rails

R = total resistance of the circuit

The capacitor equation gives the relationship between the capacitance (C) and the current to the voltage:

$$V = V(I, C; t) \quad . \tag{2}$$

A total energy balance may be written for the circuit:

$$V = V(m, \dot{x}, L, R, I, C; t) \tag{3}$$

where m and $\dot{x}$ are the mass and velocity of the propelled plasma slug. The exact form of these equations can be found in Ref. 4. Since $\dot{x} = \dot{x}(x, t)$, x and $\dot{x}$ may be interchanged in Eqs. (1) and (3). If it is assumed that the parameters L, C, and R are known or their dependence on x is known, then the three equations listed above contain four unknowns: x (or $\dot{x}$), m, I, and V. Thus, an additional relation is required in order to obtain a solution. The additional relation is, most generally, Newton's law of motion. However, the mass of the plasma slug is not well defined nor are all the forces acting on it. An alternate

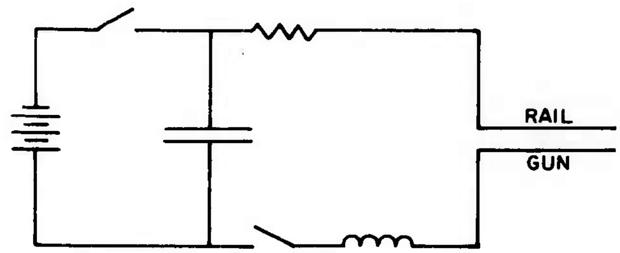


Fig. 1a. LRC Circuit

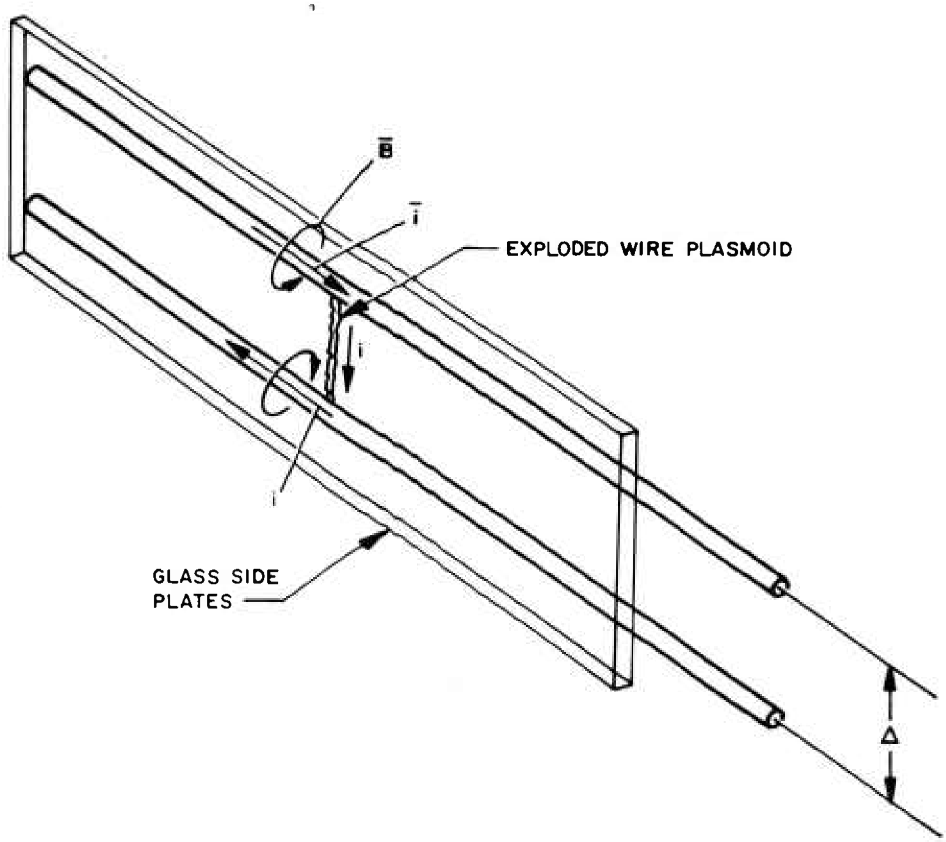


Fig. 1b. Rail Gun Propulsion Device

approach is to make some simplifying assumption relating the variables in Eqs. (1) to (3) to permit a closed form or a relatively simple numerical solution. The latter approach is discussed in the following paragraphs.

If a constant velocity assumption is made ($x/t = v$), Eq. (1) may be solved with Eq. (2) independent of Eq. (3). This was done by Steckly.

In the solution of Ref. 5, it is found that the mass of the slug must vary with time starting with zero mass at the start of the motion. This mass variation is consistent with the initial gas density distribution in some coaxial plasma guns having gas injection through high speed valves.

Another approach is to assume that the slug mass remains a constant.[4] It is well known, however, that during very high current discharges, electrode erosion is always somewhat of a problem. This electrode material certainly mixes with the propellant resulting in an unknown working mass. The uncertainty in the net mass expelled is quite large even at small erosion rates due to the minute amount of initial propellant. The elimination of electrode erosion is not the whole uncertainty since all walls will ablate or erode somewhat whether they are current carriers or not. In the case of an exploded wire propellant, the exploded material will also plate-out on all cold materials it contacts. The solution of Ref. 5 is valid if these processes of erosion and plating combine to yield an essentially constant slug mass.

Due to the shortcomings of the assumptions incorporated in the formulations, the following simplified approach has been used to reduce and interpret the experimental data obtained in the Aerospace rail gun facility. It is postulated that the net force on the plasma slug is given by $F = B_y \, i \Delta$ where the symbols are defined in Fig. 1b. Very simple magnetic theory results in the magnetic field on the axis of the rail gun to be given by $B_y = 4i(t)/10^7 \Delta$ (mks units). The net force is then $F = 4i^2/10^7$ (Newtons) where i and F are time dependent. The instantaneous impulse is given by

$$F dt = \frac{4i^2(t)\,dt}{10^7} \tag{4}$$

and the total impulse

$$I = \int_0^{t_o} F dt = \int_0^{t_o} \frac{4i^2 dt}{10^7} \tag{5}$$

where t_o is the acceleration time. Now, for an under-damped LRC circuit (where L, R, and C are independent of time), the expression for the current is

$$i(t) = \frac{V_o}{L\beta} e^{-t/\tau} \sin \beta t \tag{6}$$

where V_o = the initial voltage,

$$\beta \equiv \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \approx \frac{1}{\sqrt{LC}} , \text{ and } \tau = \frac{2L}{R} . \tag{7}$$

This form for the current discharge will be shown to be essentially correct from the experimental results presented below.

Thus, for the case where L, C, and R are independent of time, the expression for the impulse can be integrated. The resultant integration yields

$$I = \frac{V_o^2}{10^7 L^2 \beta^2} \frac{\tau}{1 + (\beta \tau)^2} \left[(\beta\tau)^2 \left(1 - e^{-2t_o/\tau} \right) + \cos 2\beta t_o - 1 - \beta\tau \sin 2 \beta t_o \right] \tag{8}$$

Since this in an under-damped sine wave,

$$\tau >> \frac{1}{\beta} , \quad \beta\tau >> (\beta\tau \approx 10 \text{ say}) \tag{9}$$

and

$$I \approx \frac{V_o^2 \tau}{10^7 L^2 \beta^2} \left(1 - e^{-2t_o/\tau}\right) = \frac{V_o^2 C \tau}{10^7 L} \left(1 - e^{-2t_o/\tau}\right)$$

$$\approx \frac{2V_o^2 C}{10^7 R} \left[1 - \exp\left(-\frac{2t_o}{\tau}\right)\right] \quad . \tag{10}$$

The coefficient of the bracket of Eq. (10) simply states that the impulse delivered is proportional to the stored energy and inversely proportional to the circuit resistance. The argument of the exponential gives some insight as to what must be done with the circuit parameters. One would like to make τ very small in order to eliminate the degrading effect of the exponential. Since $\tau \propto L/R$ and R must be made small in order to enhance the effect of the coefficient $(2V_o^2 C/10^7 R)$, L must likewise be made small. Thus, if one could obtain acceleration times on the order of the decay time, the exponential would only reduce the impulse by some 10 per cent.

The experimental results tend to indicate that the acceleration times are shorter than the decay times. Under this condition

$$I \approx \frac{2V_o^2 C}{10^7 L} t_o \quad , \tag{11}$$

and the need for small L and large t_o is obvious.

Figure 2 is a plot of Eq. (10) with τ/L as a parameter. If the approximation $\tau >> 1/\beta$ is not made, then a plot of I/E_o looks essentially like Fig. 2 with an oscillation of small amplitude superimposed on the lines of constant τ/L. Of course, the formulation of Eq. (1) assumes no viscous, radiation, joule heating, etc., losses, and as such it represents an upper bound on the performance.

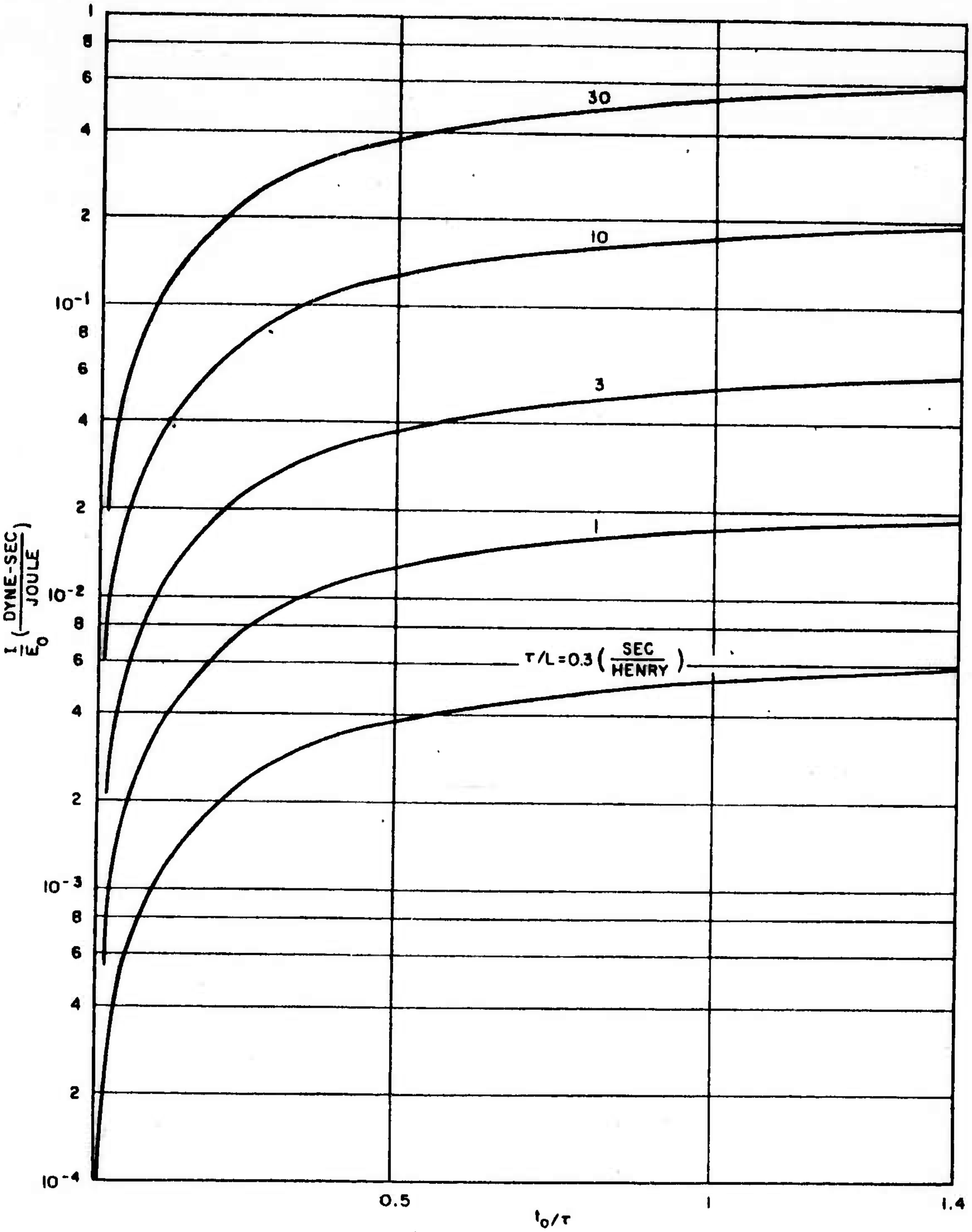


Fig. 2. Impulse Versus Acceleration Time

Equation (10) can be combined with the energy available to provide an expression for the conversion efficiency:

$$\eta = \frac{mv^2}{V_o^2 C} = \frac{Iv}{V_o^2 C} = \frac{I^2/v}{V_o^2 C} = \frac{V_o^2 C \tau^2}{10^{14} L^2 m} \left(1 - e^{-2t_o/\tau} \right)^2 \quad . \tag{12}$$

This expression is plotted in Fig. 3.

Since the rail gun system is considered here as a satellite orientation device, some estimates as to its ability to induce or reduce rotation would be in order. Since the calculations are easy to make, only the results will be presented here. It is difficult to decide what range of rotational parameters are of interest due to the large variety of applications that may be envisioned. A satellite rotational requirement may call for only a fraction of a degree per revolution about the earth, i.e., the requirement may only be to eliminate tidal effects, magnetic effects, or possibly only to maintain static antenna alignment of a 24-hour satellite. On the other hand, it may be so severe as to require a full rotation of the satellite per earth revolution. Couple this to the fact that the rotational ability of the system is a direct function of the satellite geometry and mass, and the rotational requirements become rather ill-defined for arbitrary mission and satellite geometry. Consequently, the rotational capabilities presented below cover a wide range of rotational parameters and power requirements. However, given a satellite configuration and a rotational requirement these curves should give the parameters of interest.

Figure 4 gives the single shot propulsion requirement for any increment of rotational velocity and satellite configuration. Three "classical satellites" are shown on the curve only to provide a feeling for the range of the satellite geometries presented. Figure 5 allows an estimation of the power required for a given satellite, given propulsion system, given rotational requirement, and time to rotate. The amount of power required for the application of a large rotational increment is surprisingly small. Consider the rail gun system

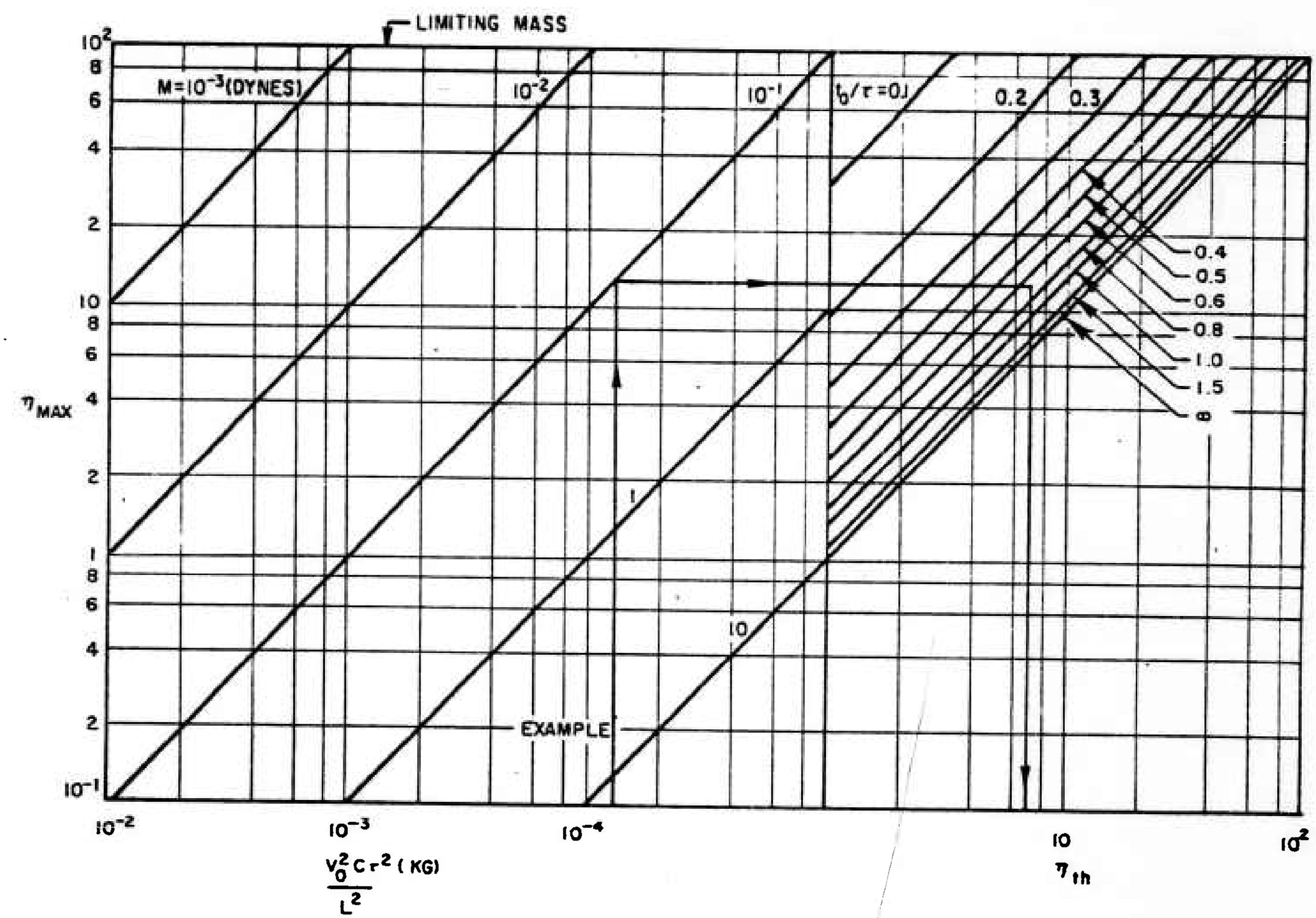


Fig. 3. Rail Gun Efficiency

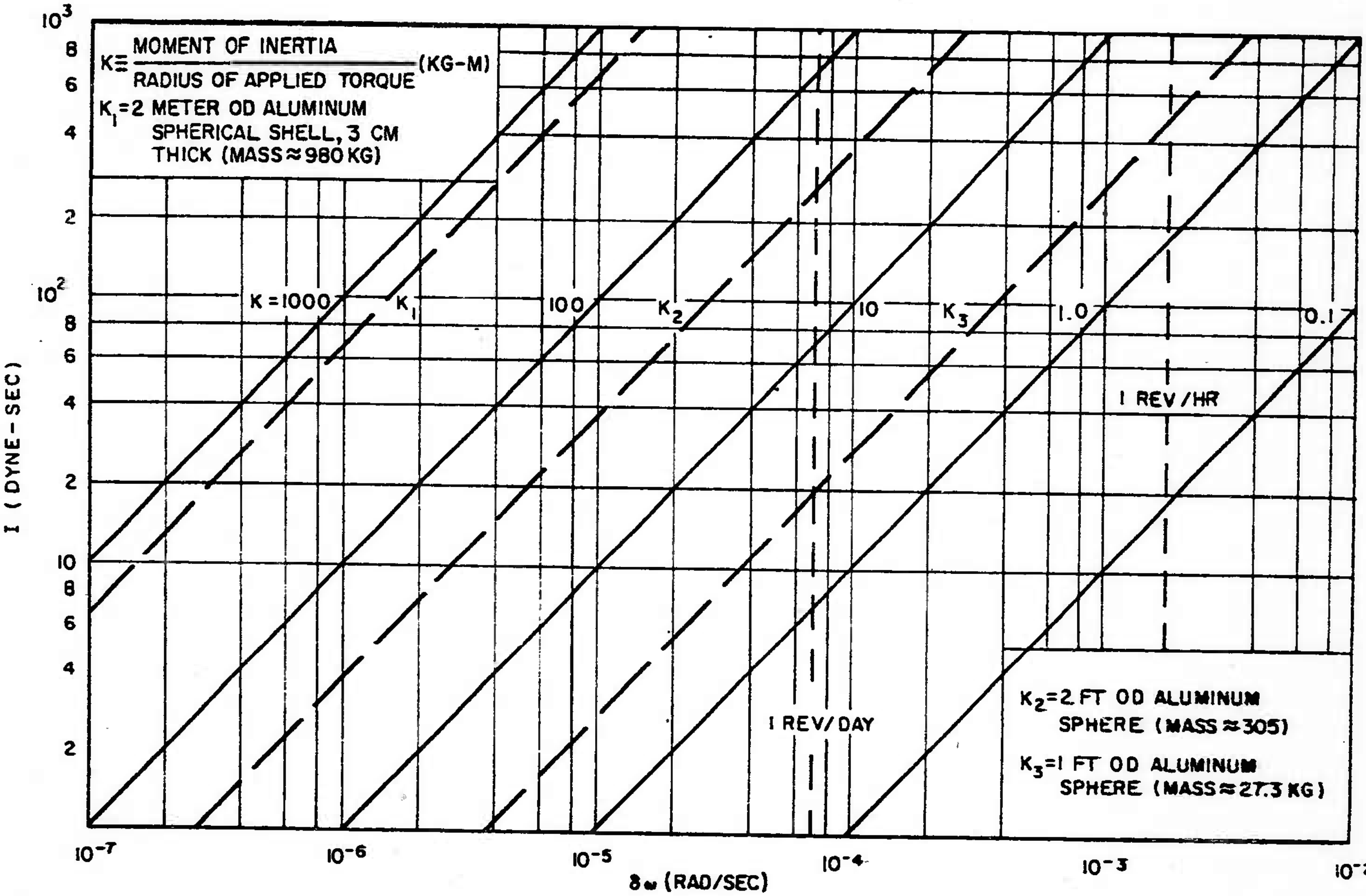


Figure 4. Satellite Torque Requirements

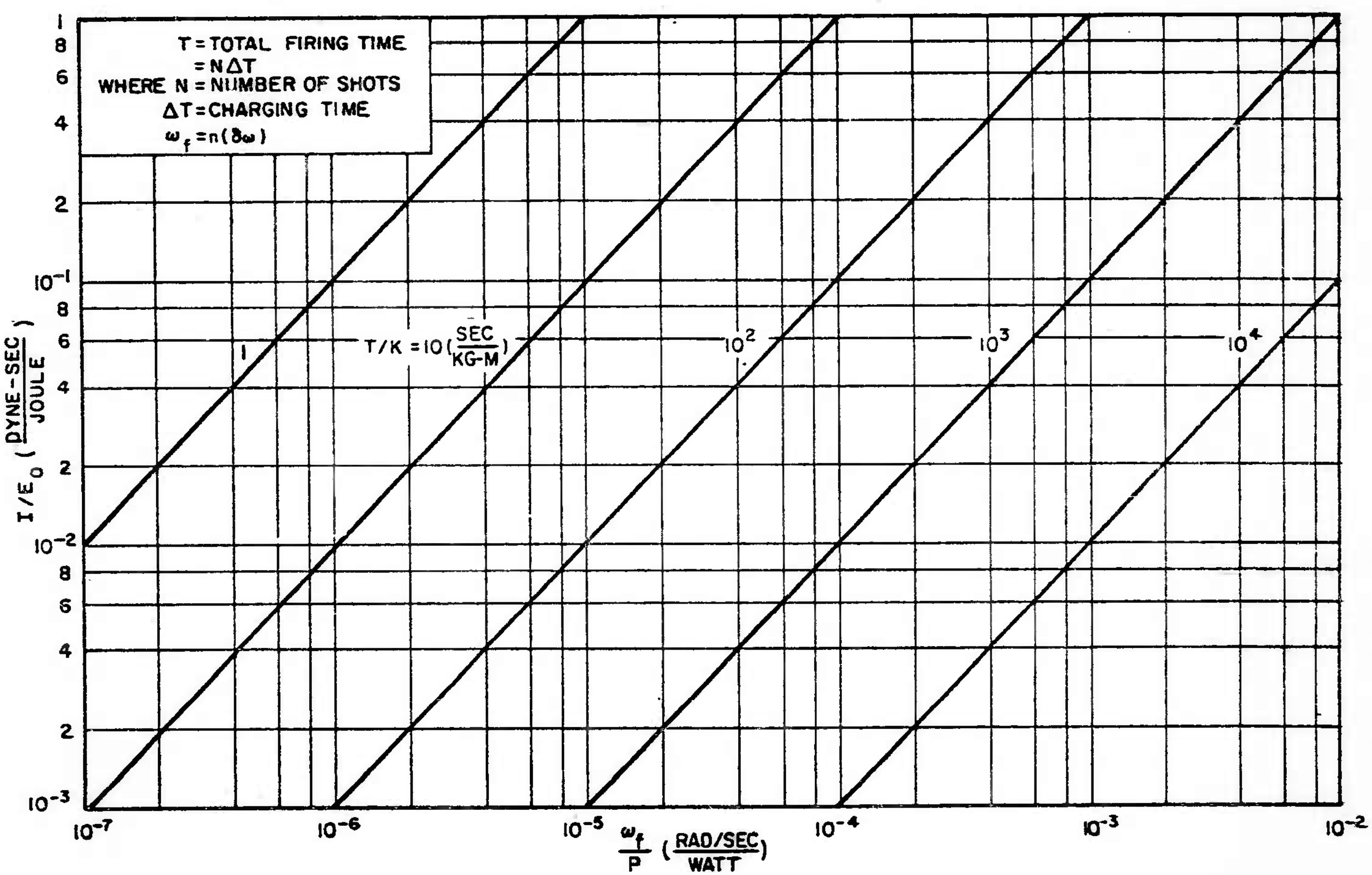


Fig. 5. Power Requirements

described below to give an impulse of 200 dyne-sec from 600 joules of stored energy ($\eta \approx$ 30 per cent). Let us require that the firing time be 30 minutes to achieve a rotational velocity of one revolution per hour for a k_1 satellete (Fig. 4). Figure 5 gives a $\omega_f / P \approx 9 \times 10^{-6}$ or $P \approx (2 \times 10^{-3})/(9 \times 10^{-6}) \approx 200$ watts. Since E_o = 600 joules, ΔT (firing interval) = $E_o / P \approx 600/300 = 3$ seconds and thus 600 shots are required. This is a small amount of power considering that the satellite mass is approximately 1 ton. Figure 6 gives the average angular acceleration that would result from a given power expenditure, satellite configuration, and propulsion system.

Since the performance of the system can be estimated from the above, it would be worthwhile to examine the weight requirements of the propulsion system only. The heaviest components of the system would be the capacitor and the high voltage conversion system for capacitor charging. Here it is assumed that a low voltage source of required power is available within the vehicle. Figure 7 gives the weight estimates for transformer-rectifier systems and motor-electrostatic generator systems.[6]

The capacitor weights may be easily estimated from a consideration of the capacitance formula for a parallel-plate condenser which results in

$$\frac{\text{Energy}}{\text{Weight}} = \frac{\epsilon K^2}{2\rho} \tag{13}$$

where

ϵ = permittivity of the dielectric

K = dielectric strength

ρ = dielectric density.

This formulation assumes that the plates and case weight of the capacitor are negligible. The result is plotted in Fig. 8 with some typical solid dielectric materials.

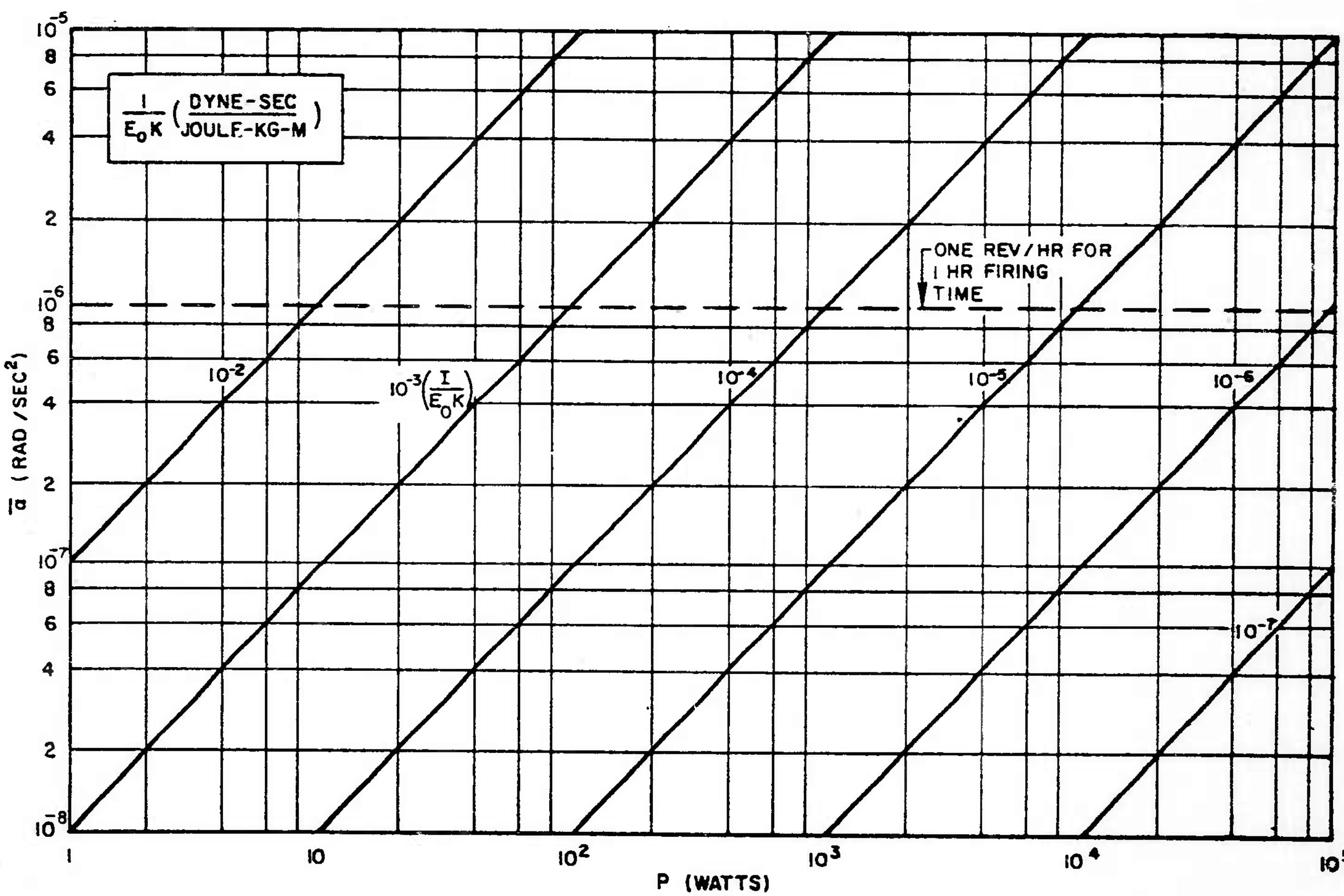


Fig. 6. Angular Acceleration Versus Power In (100 per cent efficiency)

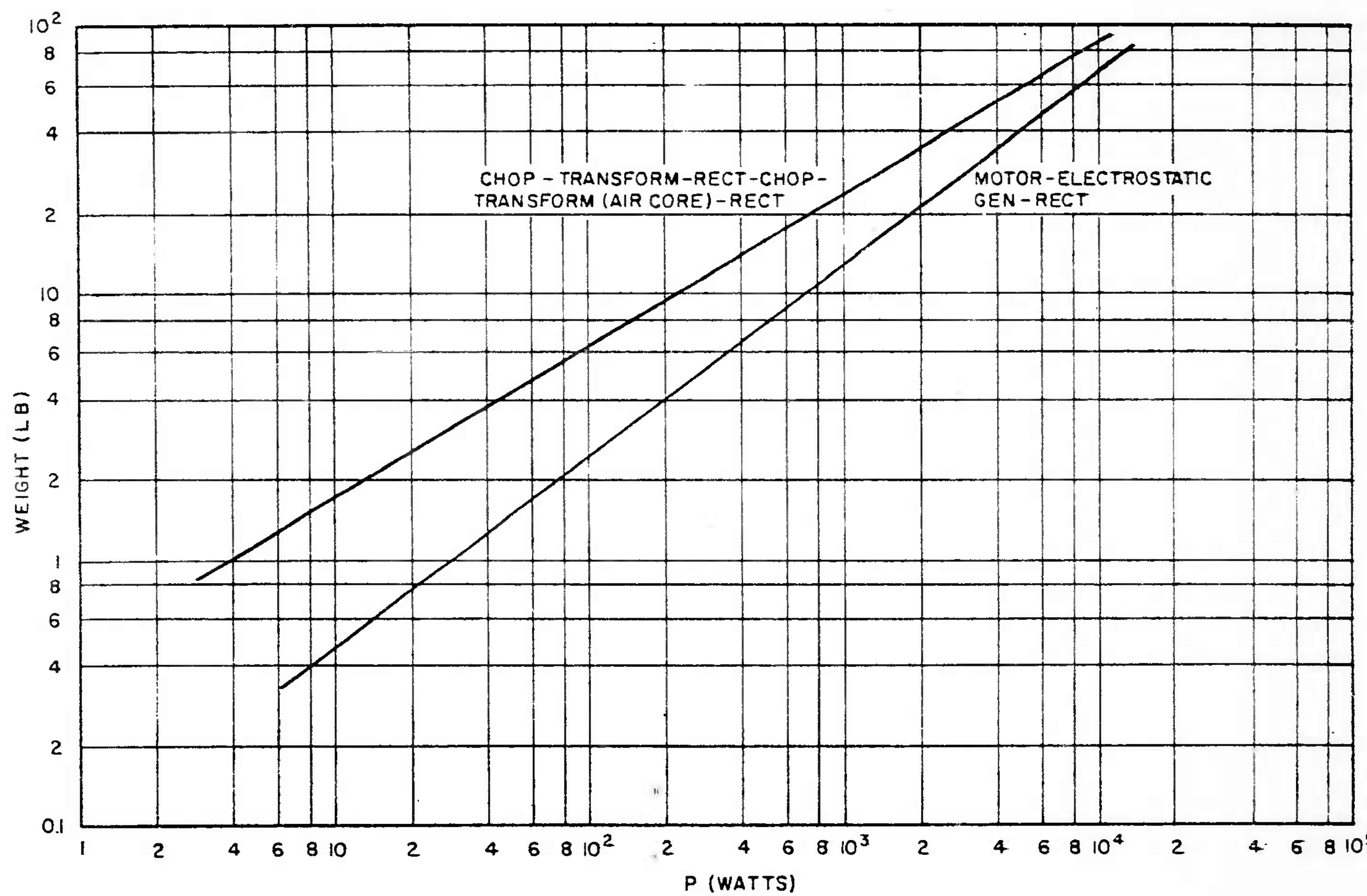


Fig. 7. Power Cut Versus Weight

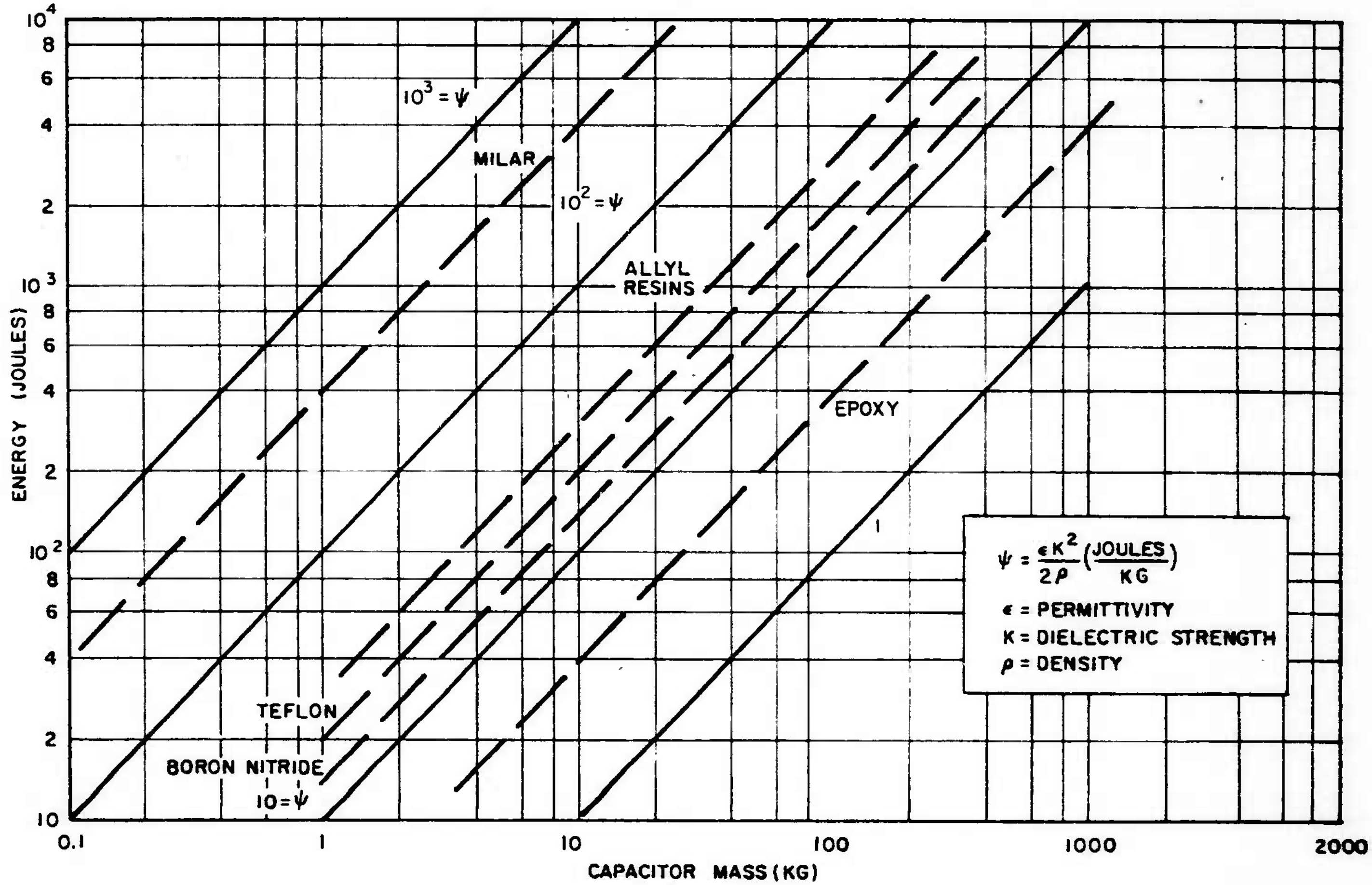


Fig. 8. Capacitor Weight Versus Stored Energy

The above results assume that the capacitor is charged to the dielectric strength limitation. This will be the case regardless of the charging voltage level. To minimize capacitor weight, high charging voltages should be used since $E_o \propto CV^2$ and C or V are proportional to the capacitor weight. This high voltage lends itself well to the insulation qualities of free space.

From Figures 4 through 8, it is now possible to estimate the weight, the power requirements, and the attitude controlling capability of a pulsed plasma propulsion system, given the propulsive capability of the device. While an estimate has been made of the propulsion parameters of a rail gun, it is highly desirable to compare this estimate with the performance of an actual gun. [An insight as to which parameters to measure is given by Eq. (10).] The total impulse, decay time, and acceleration time are of interest. From Eq. (12), an efficiency can be computed if the mass ejected from the gun or the velocity of the ejected mass can be determined.

A schematic of the instrumentation used with the rail gun experiment is shown in Fig. 9. The decay time is determined from the pickup on a loop which produces a signal proportional to the time derivative of the current. An integration then allows a voltage signal proportional to the current to be displayed on an oscilloscope. Shown in Fig. 10a is a typical current trace. The capacitance used in the bank is 1.5 μfd, so the total inductance ($L \approx 0.825$ μh) of the circuit can be determined from the frequency. This ringing frequency has remained constant establishing that C and especially L remain constant. A calculation of the rail inductance gives $L_{rail} \approx 0.04$μh and $L_{rail}/L_{circuit} \approx 0.04/0.8 << 1$ so the above result is to be expected. Another point of interest is that the current rise times during the first half-cycle are somewhat greater than 10^{10} amp/sec. The shape of the discharge current curve also gives information relative to the effective resistance of the gun since the decay time is $\tau = 2R/L$. If R varied with t, then the discharge curve would not have the characteristic exponential decay. All runs to date have resulted in this typical decaying exponential indicating that R is constant. However, there has been a slight change in the magnitude of

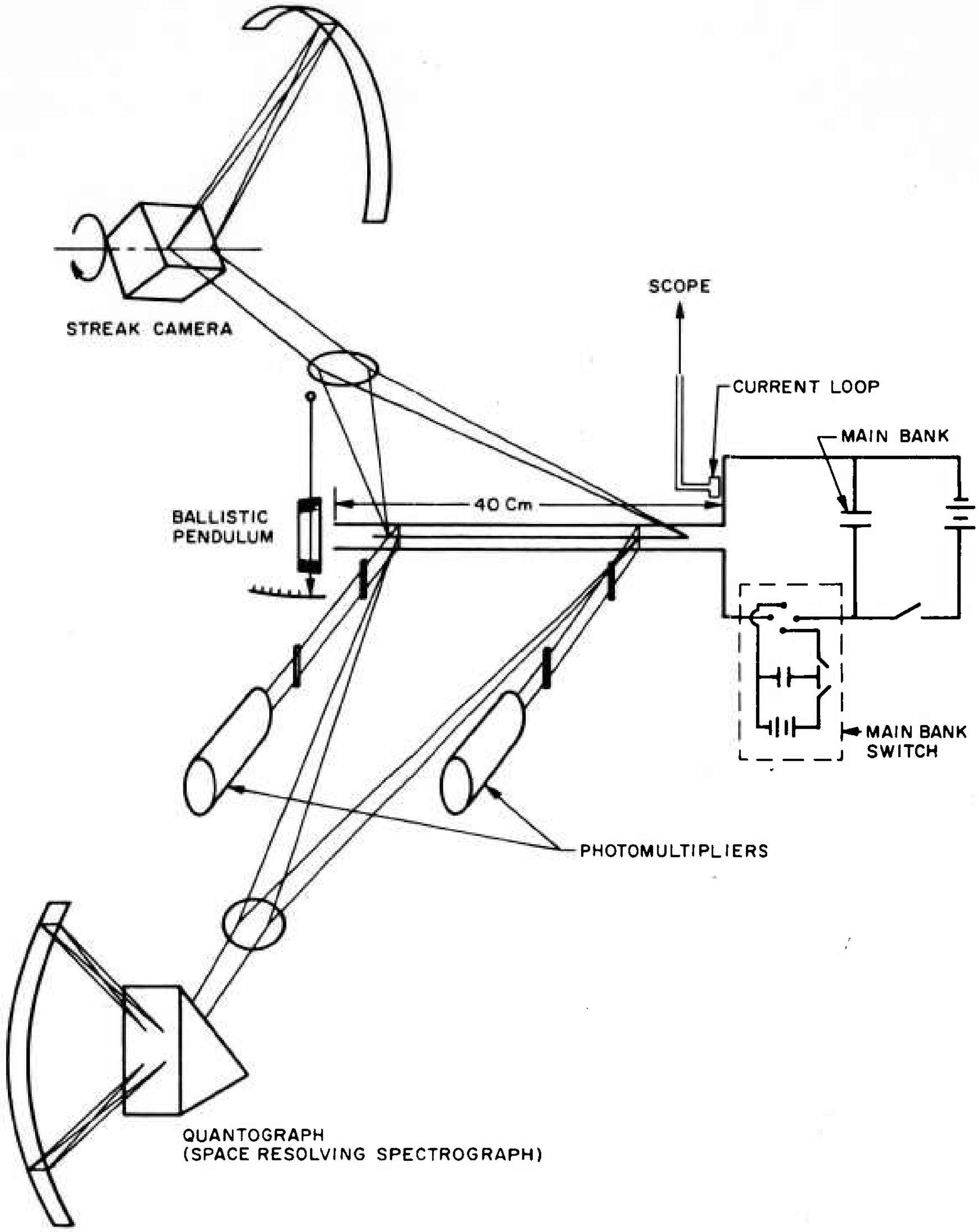
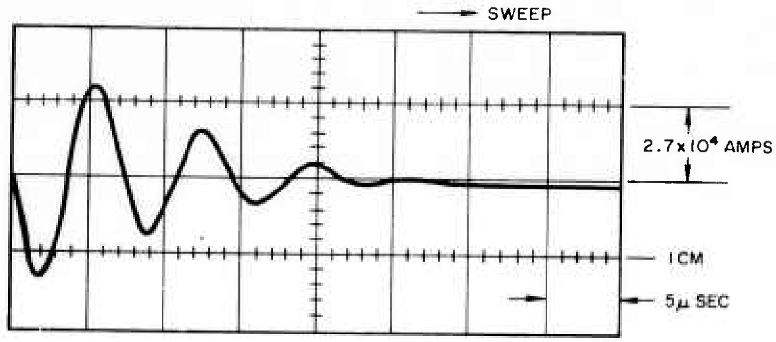
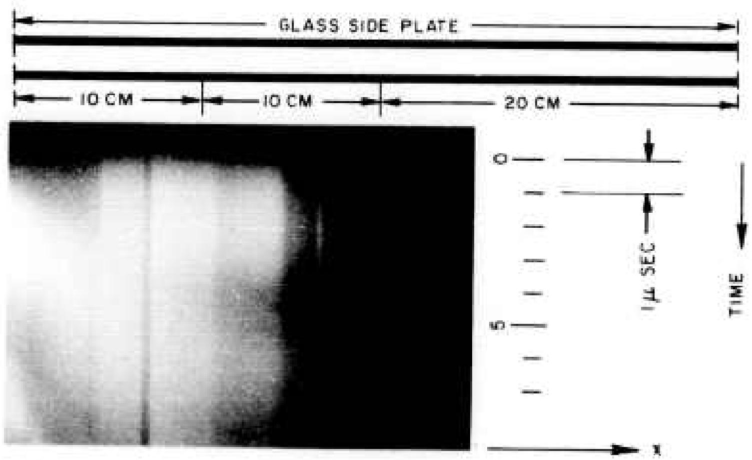


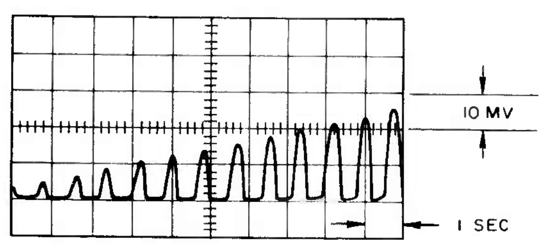
Fig. 9. Rail Gun Instrumentation



(a) CURRENT DURING DISCHARGE (τ = 11.3 μ SEC)

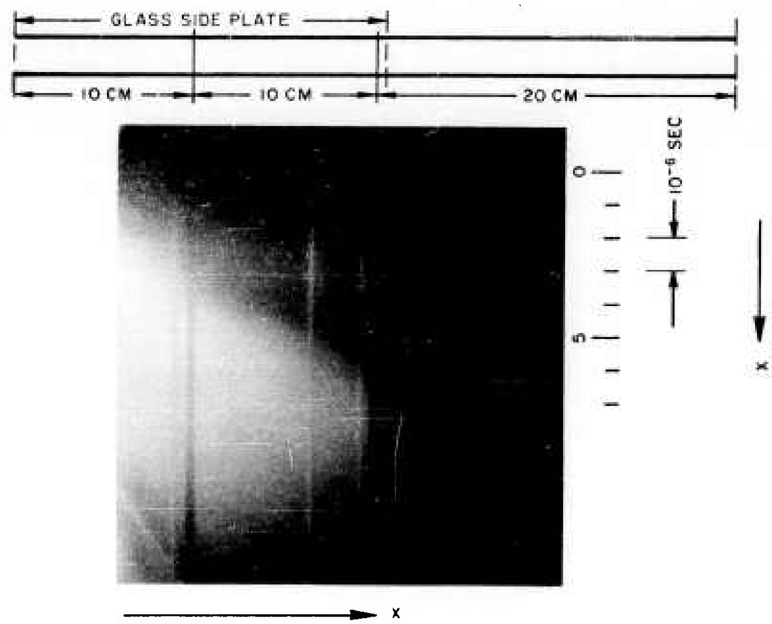


(b) STREAK CAMERA PHOTOGRAPH - LUMINOUS VERTICAL AREA DUE TO REFLECTED LIGHT (NEL $\approx 4 \times 10^6$ CM/SEC)

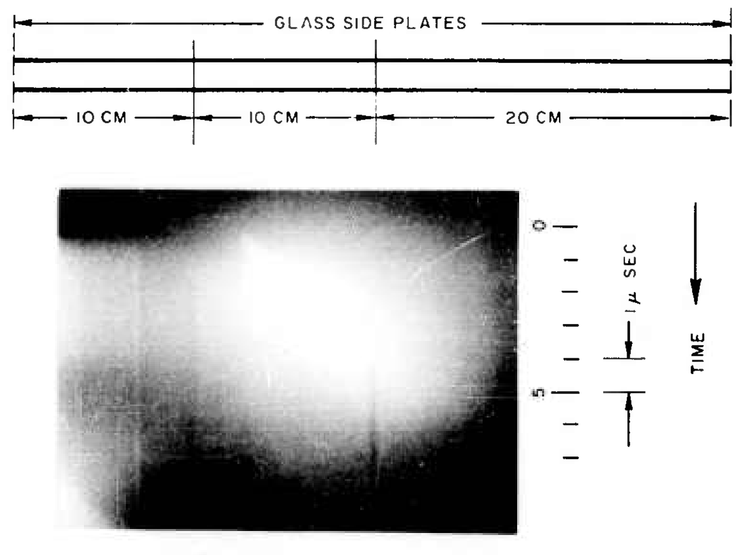


(c) IMPULSE PENDULUM TRACE (DECAY THE RESULT OF FRICTION IN SUSPENSION SYSTEM) $I \approx 0.3$ DYNE-SEC/MV

Fig. 10. Rail Gun Instrumentation Results.



(d) STREAK CAMERA PHOTOGRAPH - NOTE ATTENUATION AFTER 2ND BLACK STREAK (MARKER)



(e) STREAK CAMERA PHOTOGRAPH - NO WIRE INSTALLED. DISCHARGE SHOWN UTILIZES SIDE WALLS OF ELECTRODE AS EXPELLANT

Fig. 10. Rail Gun Instrumentation Results (continued)

the decay time with stored energy and gun configuration from shot to shot; thus, the effective resistance of the gun changes slightly from shot to shot but is constant for any one shot.

The time of propulsion (t_o) and the velocity is measured by a streak camera with a maximum writing speed of 4 mm of "film travel"/μsec (Fig. 10b). The time t_o is taken as the time before a marked attenuation in the velocity is noted. In most cases this occurs at the end of the first half wavelength. The velocity is found from a measurement of the slope of the forward edge of the luminous front of the slug, i. e., $V = \Delta x/\Delta t$.

The impulse is measured by a ballistic pendulum mounted at the end of the rails. The amplitude of the pendulum swing is determined by the interruption of a light beam on a photo cell or solar cell, whose output is displayed on an oscilloscope (Fig. 10c). The pendulum has a sensitivity of 23 dyne-sec/cm of swing. The photo cell gives a maximum sensitivity of less than 1 dyne-sec.

Some general remarks about the facility are in order. The entire rail gun is in a vacuum (average pressure $\approx 2 \times 10^{-5}$ mm Hg). The capacitor bank is 1.5 μfd so that as the charging voltage varies from 20 to 30 kilovolts, the stored energy varies from 300 to 675 joules. The copper wires are 0.001 inch in diameter and have a mass of approximately 10^{-3} grams. Such a wire requires $\approx$ 20 joules to completely melt, vaporize, and heat to 10^4 °K and singly ionize. Thus, one would expect the efficiency to increase with increased voltage. The switch (Fig. 9) utilized to switch on the charged capacitor bank is a homemade ignitron. It consists of four electrodes, two connected to the main bank. These electrodes are spaced to hold off a 30,000 volt potential in air at one atmosphere. The secondary electrodes are spaced such that the air between them will break down when subjected to a 5000 volt potential. The 190 joule, secondary capacitor bank is charged to 5000 volts and placed across the electrodes by a conventional thyratron. The secondary bank then ionizes the air inside the switch (which requires some 70 joules) and allows the discharge of the main bank.

The intent has been, throughout the course of experimentation, to optimize the rail length and spacing with respect to the measured impulse. The performance analysis presented above contained no dissipative processes (mass, momentum, and energy losses to rails and side plates) other than the circuit resistance. Losses, other than through circuit resistance, are difficult to account for analytically. Hence, the optimization is to be obtained experimentally. In particular, the optimization process is a play-off of the losses against the acceleration forces. The rails and side plates should be terminated when the retarding forces begin to dominate over the accelerating forces. The original rail length was chosen to be sufficiently long to ensure that the dissipative process dominates. Once this was established, a step-wise shortening of the rails accompanied by an impulse measurement would reveal the optimum rail length.

The original rail length was 40 centimeters, and some 50 instrumented runs were made with various rail spacing and charging voltage. These were made with and without 40 centimeter side plates, with 40 centimeter side plates of various materials and, for cases where side plates were used, with and without the wire propellant. For those cases where side plates were not used, no impulse was observed. For 40 centimeter side plate shots, small impulses (almost unmeasurable) were occasionally observed for cases where wires were exploded. Surprisingly, impulses ($\approx$ 10 dyne-sec) were observed on a few occasions when no wires were exploded; this situation will be discussed later. Drum camera pictures indicated (Fig. 10b) that the lack of impulse was due to an attenuation of the material and velocity going down the gun. Initial velocities were quite satisfactory ($\approx 3 \times 10^6$ cm/sec); however, illuminosity attenuation was complete some 25 to 30 centimeters down the gun. The later observations confirmed that the performance could be improved by shortening the rails.

Before this was done, approximately ten runs were made with shorter (20 centimeters) side plates but with full length (40 centimeters) rails. A measurable impulse was obtained; however, a velocity attenuation was noted at the end of the side plates (Fig. 10d). With the gun in this configuration, enough runs were made to give some data with the knowledge that this data may be far from the optimum

that may be obtained. This data is presented in Figs. 11 and 12. The maximum current behaves properly with respect to charged voltage. This is to be expected since it is simply the current resulting from an LRC discharge. The impulse is at least tending in the right direction (i.e., $I_A \propto V_o^2$); however, the ratio of attained to calculated impulse is off by some factor of 20. Recalling that dissipative (retarding) forces were neglected, this result is not too surprising. The velocity seems reasonably well behaved rising monotonically with stored energy.

The ratio of the measured impulse to the stored energy should be a constant by Eq. (10). The experimental data of Fig. 12 do not demonstrate this trend. The reason for the discrepancy is not presently understood. Since so few experimental points are involved, an explanation will not be attempted until more results are obtained. Lastly, the efficiencies are very low, but this is not unreasonable when the large dissipation region of operation is considered. At first, the fact that $I_A/I_o \approx 5$ and $\eta \approx 0.2$ may seem strange, since both are indicative of system performance, is because one parameter is concerned with forces and the other with energy. Note, however, that since $I_A/I_o \propto I_A$ and $\eta \propto I_A v \propto I_A^2$ that an increase in I_A/I_o by a factor 10 should be accompanied by an increase in η by a factor 10^2.

Thus, the data presented above, in the main, give evidence to the fact that the rail gun performance will improve with reduced rail length. This is now being done, and runs will soon commence using 20 centimeters rails.

The shorter rails were also indicated by the high impulse, no propellant runs mentioned previously. The streak-camera results from such a run are shown in Fig. 10e. Note that a single discharge has occurred about half way down the rails. After several such runs, an etching and pitting of the glass side plates occurred in the discharge region ($\approx$ 25 cm) indicating that the propellant producing the impulse was probably wall and possibly electrode material. The large impulse simply indicated that the shorter rail gun gives better performance.

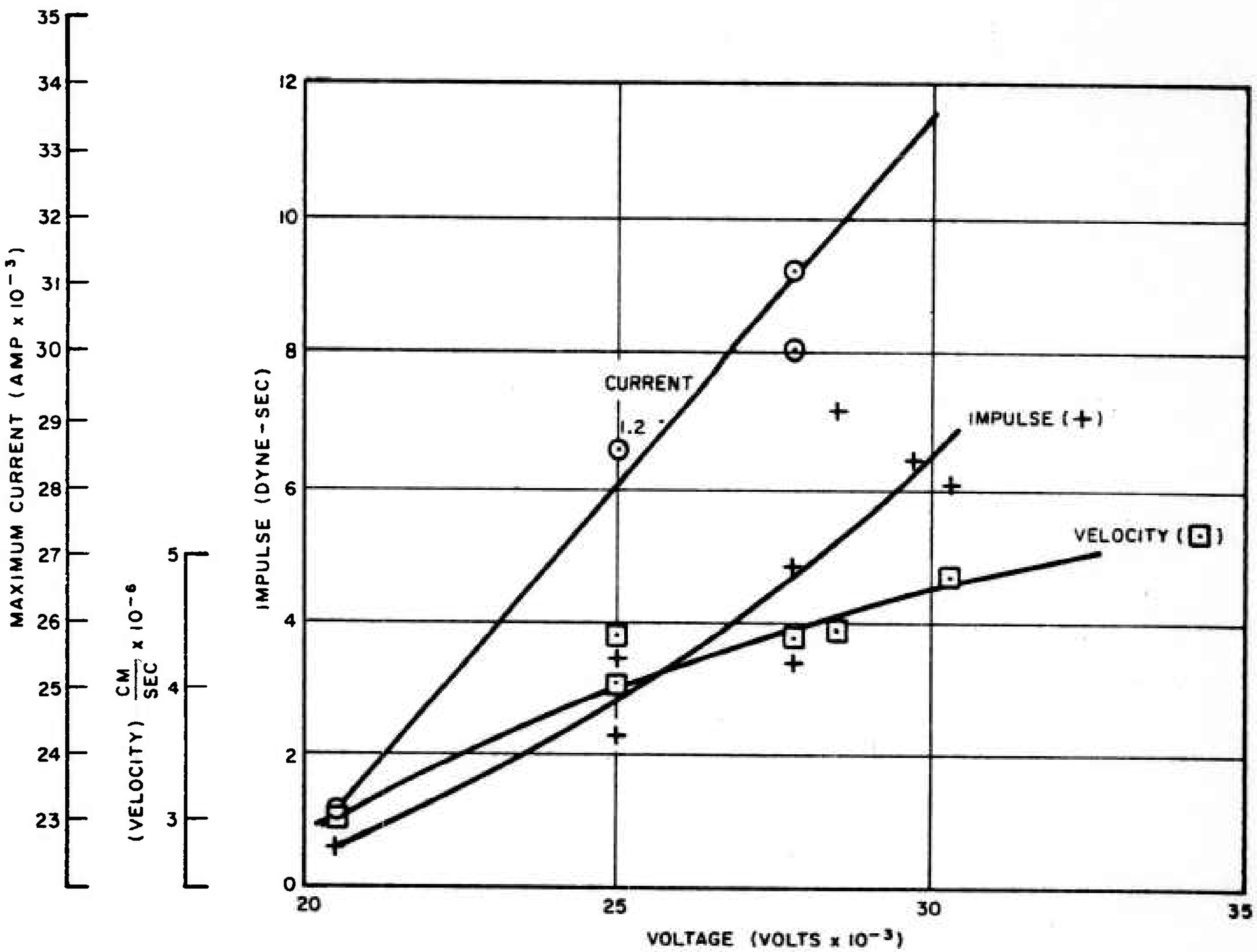


Fig. 11. Rail Gun Performance

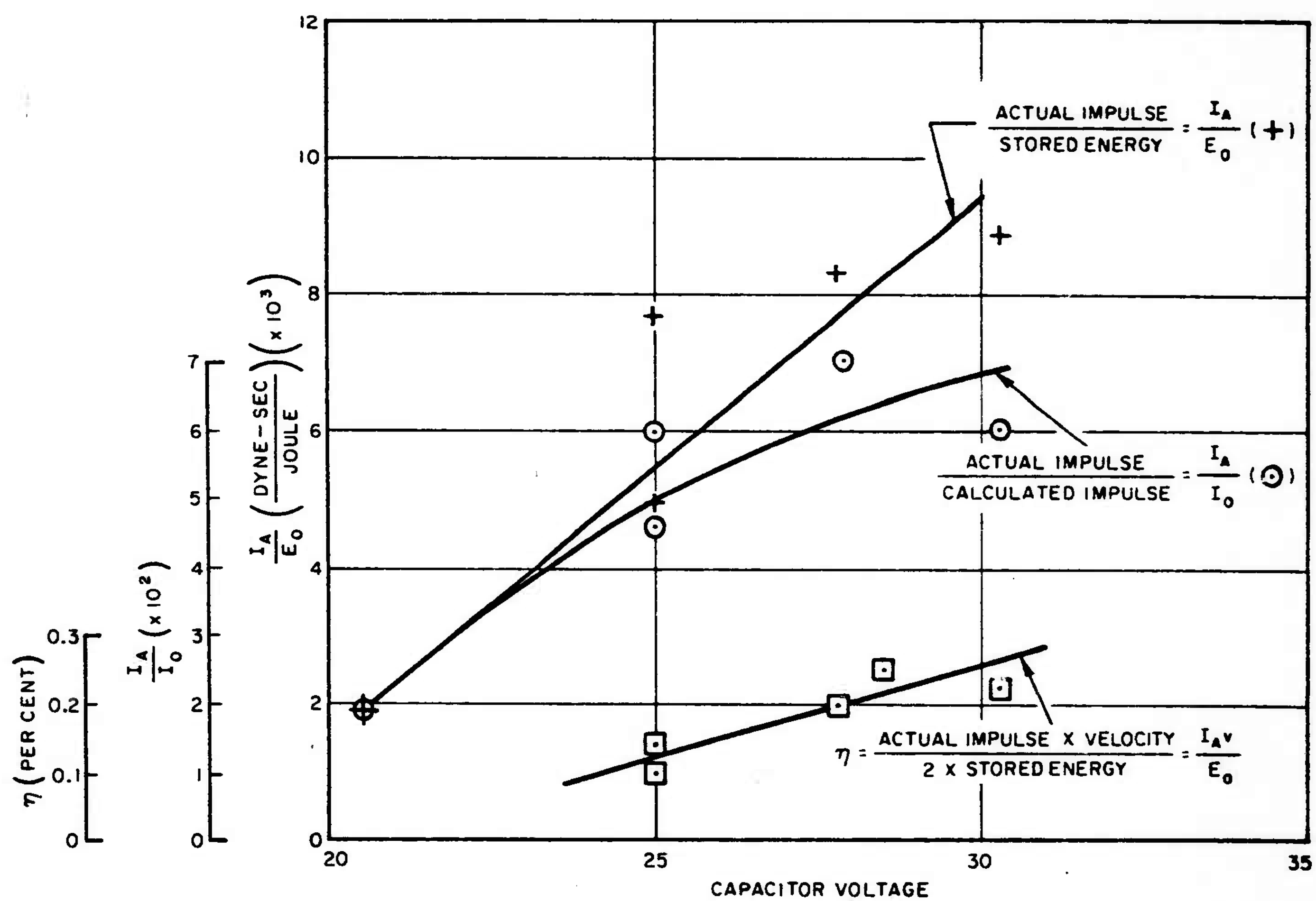


Fig. 12. Rail Gun Efficiencies

The paragraph above also points out the lack of another important bit of information (which is characteristic of all pulsed plasma devices), namely, the uncertainty as to the mass expelled and the velocity distribution of the expelled mass. For this reason, a large uncertainty exists in any efficiency measurement as defined by Eq. (12).

Some attempts are being made to obtain information relative to the distribution of the propellant down the rails as a function of time and distance. This has been attempted spectrographically as shown in Fig. 9 but with no success due to the short discharge times and somewhat longer film exposure times required. A photomultiplier and small bandpass filter are presently being considered.

Figure 13 shows a time integrated picture of the gun in operation. The two capacitors, the vacuum bell jar, and the impulse pendulum are all visible.

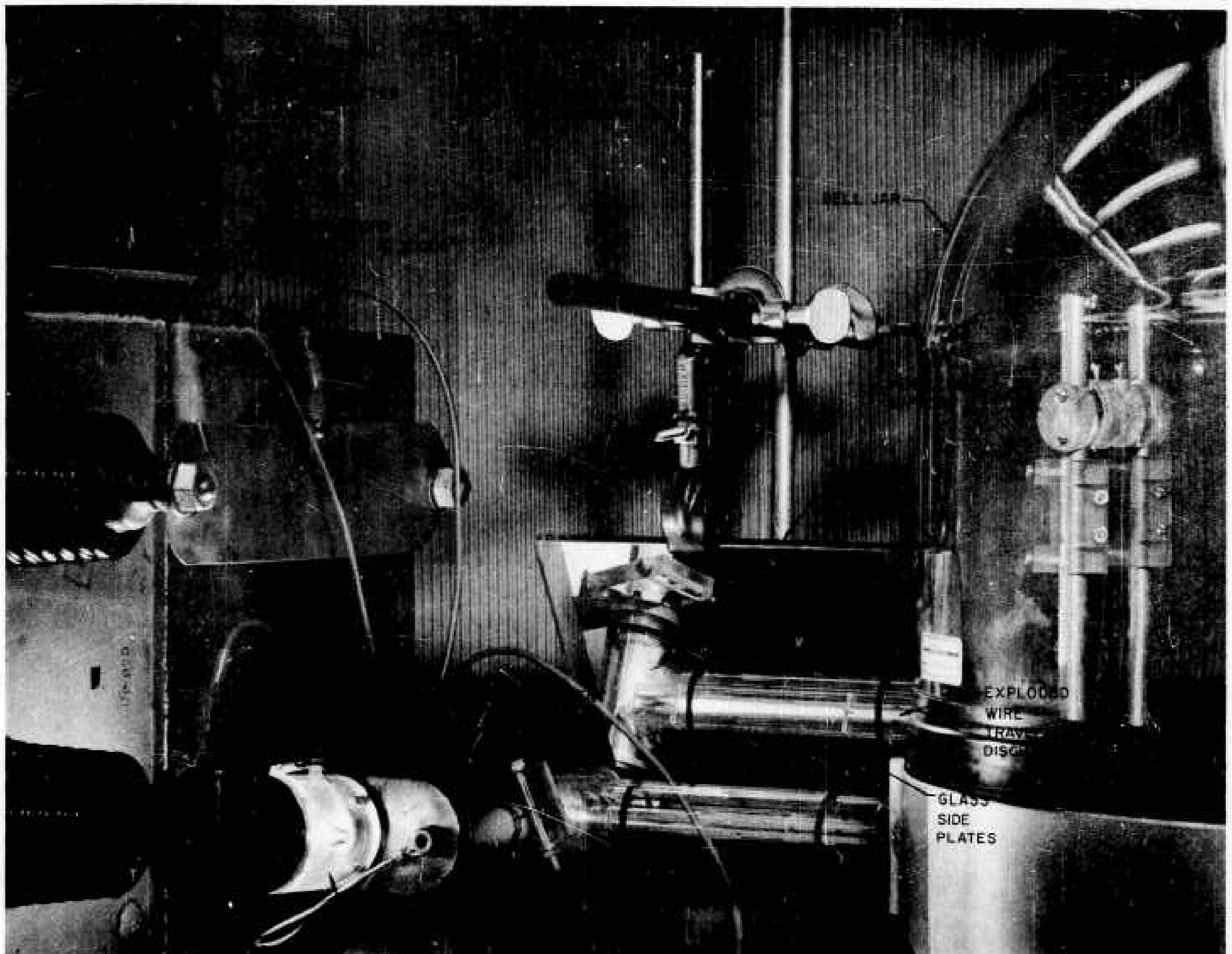


Fig. 13. Rail Gun in Operation

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